Design Development and Testing of a Bio-Inspired Robot with Caterpillar Locomotion for Pipeline Inspection

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ABSTRACT

The inspection of iron and steel pipes in industrial settings is a critical aspect of ensuring structural integrity and preventing potentially catastrophic failures. Traditional inspection methods have limitations in terms of accessibility and speed. This paper presents a novel solution in the form of a caterpillar robot designed for inline inspection of iron and steel pipes. The caterpillar robot's design, integration of advanced sensor technology, navigation, and control systems are described in detail. The paper also discusses the algorithm used for corrosion and crack detection. Results from comprehensive testing demonstrate the robot's ability to detect defects with high accuracy and reliability, thereby improving maintenance and repair decisions. The caterpillar robot offers a promising alternative to traditional inspection methods, with potential applications in various industrial contexts. This paper sheds light on the development and potential adoption of caterpillar robots for enhanced pipe inspection in iron and steel industries.

The heart of the system lies in the integration of image processing techniques. The robot employs machine vision, enabling the detection and precise identification of defects within the pipe's inner surface. A prototype model is developed, featuring caterpillar-like legs driven by electromagnetic mechanisms, allowing it to move efficiently within the pipe. The robot's image processing capabilities are realized using a Raspberry Pi camera

The image processing aspect of the project involves a range of transformations, including image blurring, smoothing, binary conversion, canny edge detection, logarithmic transformations, and contouring. These techniques are used to process captured images, providing valuable insights into the condition of the pipe. The results obtained from this research are instrumental in assessing the current state of the pipe, aiding in the early detection of potential issues, and thereby preventing costly and disruptive pipe failures

Keywords: In-Pipe Inspection Robots, Raspberry Pi camera, Image processing

1.0 INTRODUCTION:

The inspection of iron and steel pipes within industrial settings is of paramount importance for ensuring the continued safe and reliable operation of infrastructure. Pipelines constitute a critical component of various industries, including energy, transportation, and manufacturing. However, the inspection of these pipelines presents a significant challenge due to the often harsh and inaccessible environments in which they are situated. Traditional inspection methods, such as manual inspection and stationary monitoring, have their limitations in terms of accessibility, efficiency, and accuracy, leaving room for innovation and technological advancement.

This paper addresses the pressing need for improved inspection methods by introducing a caterpillar robot designed for inline inspection of iron and steel pipes. The conventional inspection techniques, including visual inspection, ultrasonic testing, and magnetic particle inspection, can be labor-intensive, time-consuming, and error-prone, particularly when dealing with extensive networks of pipes. Furthermore, these methods may fall short in detecting early signs of corrosion, defects, or structural weaknesses, potentially leading to costly repairs and critical incidents if not identified in a timely manner.

The development of robotic solutions for pipe inspection has gained significant attention over the years, aiming to overcome the limitations of human-based methods. Caterpillar robots, with their modular and adaptable designs, have emerged as a promising alternative. These robots can navigate the challenging internal environments of pipes with ease, providing a versatile platform for integrating advanced sensor technology, data analysis algorithms, and control systems to enhance inspection capabilities.

This paper delves into the design, development, and practical application of a caterpillar robot for iron and steel pipe inline inspection. It explores the components, materials, and propulsion systems used in the robot's construction, as well as the sensors employed for collecting inspection data. The algorithm for data analysis and defect detection is discussed in detail, along with the navigation and control systems that ensure precise movement within the pipes.

Through comprehensive testing and real-world case studies, this paper aims to provide empirical evidence of the caterpillar robot's capabilities in detecting defects, corrosion, and structural anomalies. The results of these experiments demonstrate the potential of caterpillar robots to significantly improve inspection accuracy, speed, and reliability, ultimately enhancing maintenance and repair decision-making processes.

As we embark on an era where technology plays an increasingly pivotal role in infrastructure management, the development and deployment of caterpillar robots for iron and steel pipe inspection represent a noteworthy advancement in ensuring the integrity of critical pipelines. This paper offers valuable insights into the evolving landscape of inspection methods in the iron and steel industry and the potential benefits of integrating caterpillar robots into existing inspection practices.

2.. LITERATURE REVIEW:

2.1. **Various other robotic Pipe Inspection technologies**.

A literature review on other robotic inspection technologies will help provide context for this technical paper on caterpillar robots for iron and steel pipe inline inspection. Here are some of the notable robotic inspection technologies and the existing research and developments in the field:

2.2 Pipeline Inspection Gauges (PIGs):

PIGs are autonomous devices that travel through pipelines for inspection and maintenance [1] They are equipped with various sensors, such as magnetic flux leakage (MFL) or ultrasonic sensors [2] to detect defects, corrosion, and other anomalies. PIGs have been widely used in the oil and gas industry for many years. Research focuses on improving sensor technology, navigation, and data analysis.

2.3 Autonomous Underwater Vehicles (AUVs):

AUVs are used for inspecting underwater [3,4] pipelines, such as those in offshore oil and gas facilities. They can carry cameras, sonar systems, and other sensors to assess the condition of subsea pipes. Research in this area aims to enhance AUV autonomy, extend operational depth, and improve data quality.

2.4 Unmanned Aerial Vehicles (UAVs):

UAVs, or drones, have been used for inspecting above-ground pipelines [5,6], such as those in the energy and utility sectors. They can capture visual and thermal images, as well as use LiDAR or other sensors to identify issues like corrosion, leaks, or vegetation encroachment. Research is ongoing to develop more advanced inspection capabilities and autonomous navigation for UAVs.

2.5. Crawling Robots:

Crawling robots like inchworm/caterpillar robots [7] are designed to navigate inside confined spaces like pipes, tanks, and ducts. These robots often use various sensors, including cameras and lasers, for visual inspection. [8-10] Research in this area focuses on improving mobility, adaptability to different pipe sizes, and the integration of advanced sensors.

2.6. Autonomous Pipe Inspection Robots

Autonomous mobile robots offer an effective solution for this task, which involves the need for visual data from the inside of pipes along with location information for inspection. This paper [11] presents a comprehensive review of past autonomous robot designs and introduces a novel robot that emphasizes a straightforward design and seamless movement. It focuses on real-time image processing to identify anomalies within the pipes and subsequently initiates the capture of high-resolution images to manage memory constraints efficiently. The use of autonomous robots is instrumental in the examination of pipe interiors. Sewage pipelines present a formidable challenge [12] for human inspection due to their inaccessibility. It is imperative to gather data in the form of images that highlight any cracks or imperfections in the pipes.

2.7 Swarm Robotics:

Swarm robotics [13] involves the use of multiple small robots working together to inspect and monitor large areas. These systems can be applied in scenarios like environmental monitoring, agriculture, and infrastructure inspection. Research focuses on coordination algorithms and communication between swarm members.

2.8 Remote Inspection in Hazardous Environments:

Robots are deployed in hazardous environments, such as nuclear facilities and chemical plants, to inspect and maintain equipment. These robots need to withstand extreme conditions [14] and may use specialized sensors like radiation detectors. Research is centered on developing robust and reliable solutions for high-risk environments.

By reviewing the literature on these robotic inspection technologies, I can highlight the diversity of approaches in the field and demonstrate how caterpillar robots offer a unique set of advantages, particularly in the context of iron and steel pipe inline inspection. These advantages might include enhanced mobility, adaptability to varying pipe sizes, and the integration of multiple sensors for comprehensive data collection and analysis.

3. CATERPILLAR ROBOT DESIGN AND COMPONENTS

The robot model was designed in SolidWorks using a systematic process Initially, the robot's specifications were outlined, including a size of 400mm in length, 200mm in width, a linear actuating locomotion mechanism, and a payload capacity of up to 5kg. 3D models for each component were created using SolidWorks' modeling tools, which involved utilizing features like extrusions, revolves, and sweeps. These components were then assembled to form the complete robot, ensuring they fit and moved as intended. SolidWorks' motion analysis features were employed to simulate and evaluate how the caterpillar tracks would move and interact with the terrain. Details such as sensors, actuators, and other necessary components were added to the model, ensuring correct placement and orientation. Material selection for each part was determined, and considerations for manufacturing were made with SolidWorks aiding in creating manufacturing drawings. Documentation, including assembly instructions and part lists, was generated to facilitate the construction of the physical robot. A prototype was built using the design files and tested to ensure its proper functioning. Based on the prototype's performance, the design in SolidWorks was refined through iterations until the robot met the specified requirements. Once satisfied with the prototype, the design was finalized.

3. 1. Materials Used:

The Robot Model was constructed using Polylactic acid (PLA), a commonly employed material in 3D printing known for its biodegradable properties and origin from renewable sources such as corn starch. PLA boasts multiple advantages, notably its low melting point, rendering it well-suited for lightweight and user-friendly applications.

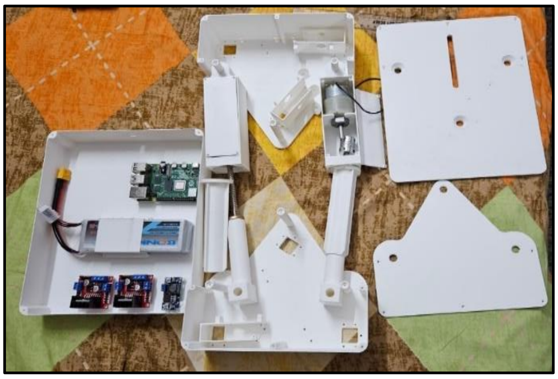

Fig 3.1.1: 3-D Printed Components

3 .2. Chassis and Body:

The caterpillar robot's chassis and body are crafted from Polylactic Acid (PLA), a favored 3D printing material, chosen for its eco-friendliness derived from sources like corn starch. PLA's adaptability in 3D printing allows engineers to create intricate custom designs crucial for the robot's functionality, despite its lightweight nature. It possesses sufficient mechanical strength to support the robot's components and withstand typical operational stresses, owing to its biodegradability and eco-friendly properties. Moreover, its low melting point streamlines the 3D printing process, ensuring smoother layer adhesion and a refined surface finish. PLA's user-friendly 3D printing process simplifies assembly and customization, with individual parts being printed separately for convenient repairs or upgrades. Although it may not be the most wear-resistant material, additional surface treatments can enhance its durability. Furthermore, the availability of PLA in various colors facilitates aesthetic customization of the robot's appearance, and its compatibility with other materials makes it adaptable to specific design requirements.

Fig 3.2.1: Chassis and body

3.3 Robot Legs

The robot model features a unique locomotion system, utilizing electromagnetic legs with rack and pinion actuation. This innovative design enables the robot to move inside ferrous pipes, mimicking the fluid, caterpillar-like motion. Electromagnetic legs create a strong grip on the pipe's inner surface, allowing precise control and efficient propulsion. The rack and pinion actuation mechanism ensures smooth and reliable movement by converting rotational motion into linear motion, facilitating the robot's navigation through complex pipe systems. This technology not only enhances the robot's maneuverability within such environments but also makes it an ideal choice for inspection and maintenance tasks in various industrial and utility applications.

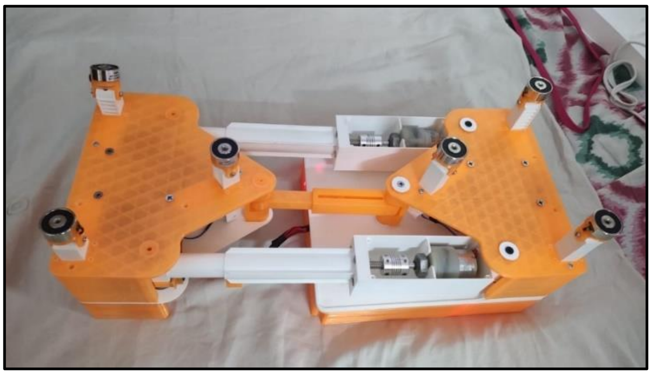

Fig 3.3.1: Robot Legs (Bottom View)

3.4 Final robot design and specification

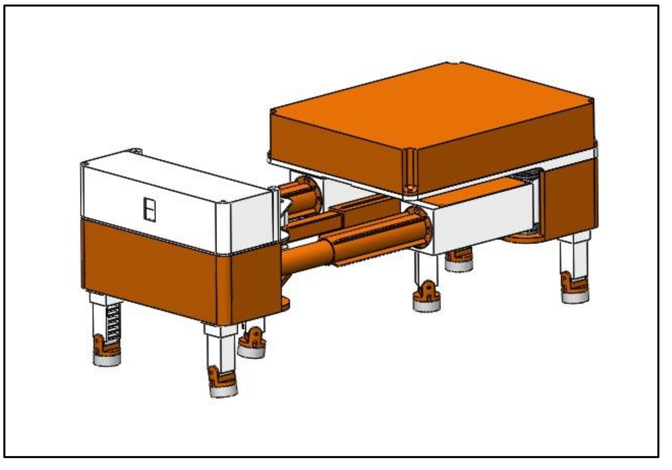

Fig 3.4.1 CAD Model of the Robot

Fig 3.4.2 Final Assembled Robot

Specification: Specifications of the Assembled model is

Length: 400mm (Before Extension)

Length:500mm (In Full Extension)

Breadth: 200mm

Weight:2.68 Kgs

4.0 SENSORS AND ELECTRONICS USED AND WORKING

4.1 Raspberry Pi with camera:

Raspberry Pi is a multithreaded minicomputer with programable GPIO's which performs image processing and identifies anomalies in the images taken from the camera attached to pi cam port. It has a Raspberrian OS with phyton code running which uses Haar algorithm to identify the cracks and rusted surfaces at specific distance travelled inside the pipe. The details of detection are annotated on the photograph itself along with time stamp and anomaly detected.

Fig4.1 Raspberry Pi with camera

4.2 Arduino Pro Micro:

Arduino pro micro is an embedded microcomputer with Atmega324p chip which has Digital and analog GPIO's for controlling peripherals. This controller is mainly incorporated in the project for controlling locomotion and sending command to Raspberry pi to take the pic and perform image processing. Arduino pro micro waits for around 30 seconds letting raspberry pi to boot its OS and ready to take a picture thru camera attached to it. Arduino is used to control the locomotion by controlling two DC motors of Robot. It also controls the servo motors attached which controls the electromagnet plungers, allowing bot to move forward with greater precision even on rough surface.

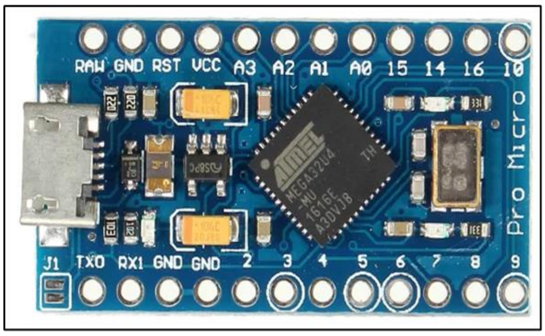

Fig4.2 Arduino Pro Micro

4.3 Electromagnets:

Electromagnets are used in the project to hold the specific segment of bot to accomplish the movement like caterpillar. When 12v power supply is given electromagnets will hold the inner surface of the metal pipe. Alternate activation of electro magnet segments in front and back side of the bot allows caterpillar movement. Electromagnets with 8kg nm at 12v are used for better grip and contact surfaces can tilt accordingly.

Fig4.3 Electromagnets

4.4 DC Motors:

Two DC motors of 60rpm each are used for locomotion driven by Dc motor driver. 3mm ball screws are attached to shafts of DC motor. When rotated the linear actuators on both sides are operated, when two motor are rotated clock wise, both linear actuators expand. Before expanding back side electro magnets are activated so that back portion make a firm grip to the inner surface of the pipe and front portion moves forward. Then front electromagnets are activated and rear electromagnets are deactivated. Now motors are rotated counter clock wise to make both linear activators contract, which moves the rear portion move forward. Same cyclic processes are looped to move bot forward and vice versa.

Fig4.4 DC Motors

4.5 L298N DC motor Driver:

L298N driver module are used to control the DC motors. The control signal generated by Arduino pro micro are just 20 ma which cannot drive dc motor directly. Low voltage and low current control signals from Arduino are to be amplified using a suitable power amplifier which can provide sufficient voltage and current to drive the DC motors. L298N IC is employed to convert any control signal to DC motor compatible voltage and current to 12v /2amps respectively.

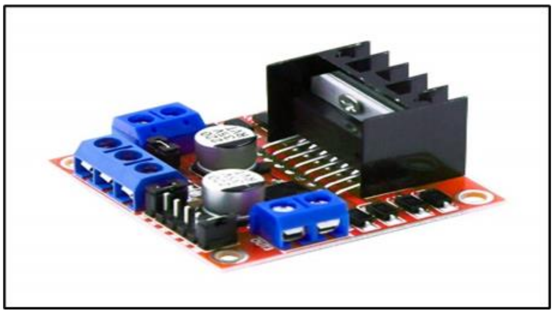

Fig4.5 L298N DC motor Driver

4.6 LM2596 DC to DC converter

LM2596 is a DC - DC buck converter which converts any voltage to specific voltage. The Raspberry pi and Arduino controllers used in the project require on 5v power supply but the Primary power source used is a 12V/ 5200mAh battery. To convert this 12v power supply to required 5v power supply, Two LM2596 modules are incorporated, one for Arduino and another for Raspberry Pi.

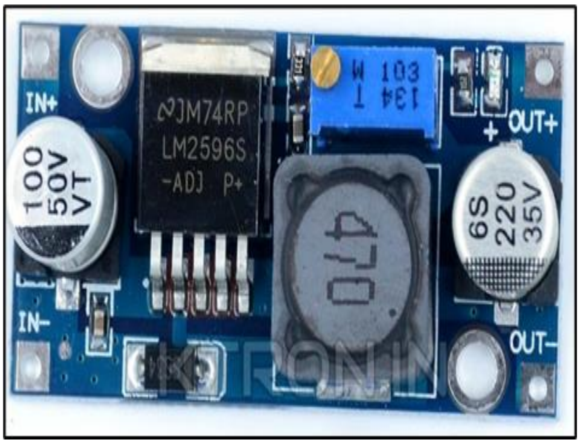

Fig4.6 LM2596 DC to DC converter

4.7 Li-Po 5200mAh Battery pack

Lithium-Polymer battery packs are highly efficient battery packs with low weight and high power for robot applications. The battery pack used here is a combination of 3 individual Li-Po battery cells with 3.7 volts each. 3 segments of battery cells will form 3S battery pack with maximum voltage of 12.8 and minimum of 11.1 v.

Fig4.7 Li-Po 5200mAh Battery pack

4.8 Servo Motors

Servo motors are highly efficient and precise in terms of mechanical accuracy. These servos used in our project provide better control over electro magnets mounted plungers move in and out which makes bot move on rough surfaces easily. Servo motors has a small DC motor and a rotary encoder which feeds the control board the signal of angle of rotation of the output shaft. Here in this work rack and pinon mechanism is used to move plungers in and out using servo motors of model SG5010.

Fig4.8: Servo Motors

4.9 HC SR 04 Ultrasonic distance sensor

The HC-SR04 is a cost-effective ultrasonic distance sensor known for its high accuracy, capable of measuring distances with precision down to 3mm. This sensor operates without physical contact and can detect objects at distances ranging from 2 cm to 400 cm. Each HC-SR04 module comprises an ultrasonic transmitter, a receiver, and an integrated control circuit. When using the HC-SR04, you only need to focus on the four pins marked as VCC (Power), Trig (Trigger), Echo (Receive), and GND (Ground). Its built-in control circuitry is designed to address issues like data inconsistency or "bouncy" readings, making it suitable for various applications.

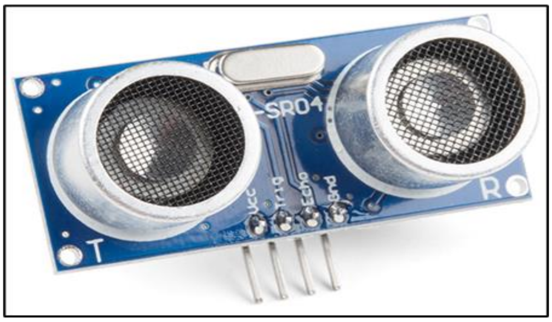

Fig4.9: HC SR 04 Ultrasonic distance sensor

4.10 Block Diagram:

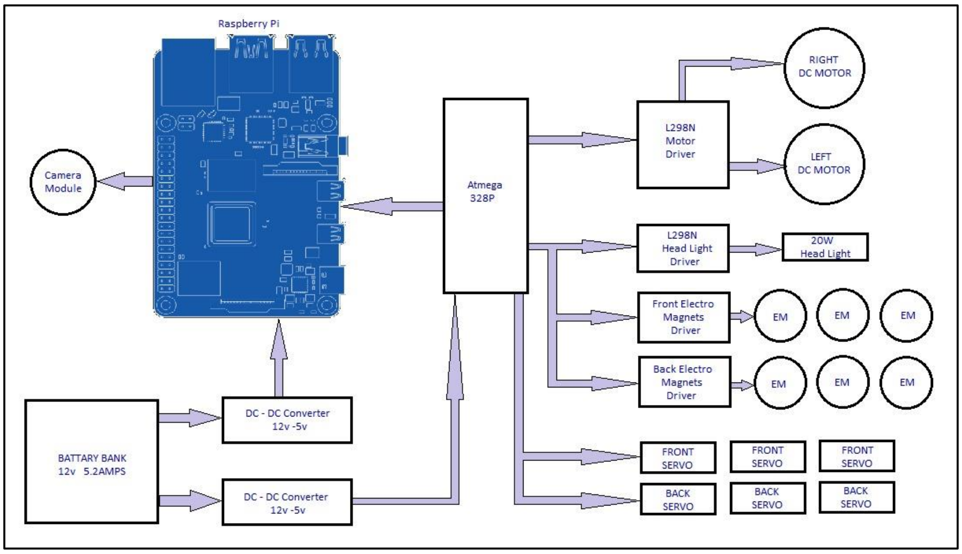

Fig4.10: Block Diagram of Robot model

4.11 Working of the Fabricated Robot Model

This autonomous robot utilizes image processing to identify cracks and rust within pipes, employing a Raspberry Pi with an onboard camera, controlled by an Arduino Pro Micro. The robot features two sets of three electromagnets at the front and rear, providing a secure grip on the pipe's inner surface, driven by a current amplifier driver. Its locomotion is powered by two geared DC motors, managed by the L298N Driver board, connected to linear actuators with a ball screw mechanism. The robot hovers and moves forward by expanding the linear actuators with CW rotation of the motors while activating servo motors attached to front electromagnets. The Arduino triggers the Raspberry Pi at GPIO 4 for image capture and analysis, with the aid of 20W headlights for clear images. The robot calculates the distance traveled based on the number of commands received, with each hover cycle covering 10 cm. A 5.2 Amps/hr Li-Po 12V battery powers the robot, with DC-to-DC converters adapting the voltage for the Raspberry Pi and Arduino. An HCSR-04 ultrasonic distance sensor aids in detecting junctions and obstacles, enabling turning maneuvers when needed. Once the autonomous pipe inspection is complete, the Raspberry Pi can connect to a TV or monitor via an onboard HDMI port, or images can be accessed through a connected pen drive.

5.0 PIPE INSPECTION (IMAGE ANALYSIS) METHODOLOGY:

5.1 Raspberry Pi image analysis technique can be used in pipe line crack and corrosion detection by analyzing the images captured by cameras installed in the pipelines. The images can be processed using image analysis algorithms to detect visual difference such as cracks and corrosion. The image analysis [15-17] algorithm can be designed to detect cracks and corrosion by analyzing the color, texture, and shape of the Variations in the images. For example, the algorithm can identify cracks by detecting linear features with high contrast in the images, while corrosion can be detected by analyzing changes in colour and texture of the pipeline surface. Raspberry Pi can be used as a platform to run the image analysis [18] algorithms and process the images. The processed data can be transmitted wirelessly to smart devices, allowing for proactive maintenance and early detection of faults.

5.2 Haar cascade classifier

OpenCV, a widely adopted open-source computer vision and machine learning library, is employed in a basic facial recognition system on a Raspberry Pi 4. In this system, a Haar cascade classifier is utilized to detect faces. OpenCV offers a range of pre-trained algorithms, making it a versatile tool for multiple computer vision applications, with facial recognition being one of them.

By applying the "Haar Cascades" algorithm for crack and corrosion detection in ferrous pipes involves a customized utilization of this computer vision technique. In this context, the algorithm is trained to discern specific visual patterns associated with cracks, corrosion, or structural anomalies on the inner surfaces of ferrous pipes. The process begins with the capture of high-resolution images or scans of the pipe's interior. The algorithm, featuring Haar-like features and a cascade of classifiers, systematically analyzes these images, progressively eliminating non-defective areas. By matching the captured patterns to pre-trained defect profiles, the algorithm accurately identifies and locates potential issues in the ferrous pipe, allowing for proactive maintenance, minimizing the risk of leaks, and ensuring the longevity and safety of the pipeline infrastructure in various industrial applications.

5.3. Crack and Corrosion Detection

Using the "Haar Cascades" algorithm for identifying defects in pipes involves a creative adaptation of the technology. In this scenario, the robot is equipped with a camera or sensor to capture images or scan the interior of the pipe. Instead of searching for human faces, the Haar cascades are trained to recognize distinctive patterns, textures, or features associated with pipe defects like cracks, corrosion, or anomalies.

Image Capture: The robot captures images or scans the inner surface of the pipe as it moves along its path.

Haar-like Features: The algorithm employs Haar-like features, which are essentially simple rectangular patterns used to describe various aspects of the image. These features are carefully designed to represent the characteristics of pipe defects.

Cascade Classifier: The Haar cascades consist of multiple stages, each with a set of weak classifiers. At each stage, the algorithm evaluates the image region using the Haar-like features to determine whether it exhibits characteristics of a defect or not.

Detection Process: The robot's software processes the image data, examining different regions of the pipe at various scales. It progressively filters out regions that do not resemble pipe defects.

Defect Identification: When an image region passes through all stages of the cascade classifier, it is identified as a potential defect in the pipe.

Alert or Data Collection: Once a potential defect is detected, the robot can alert operators in real-time for immediate action or collect data for later analysis and maintenance.

This innovative application of the Haar Cascades algorithm helps in the early identification of defects in pipes, enabling proactive maintenance and ensuring the integrity and safety of the pipeline infrastructure. The algorithm is highly adaptable and can be trained to recognize a variety of defect patterns, making it a valuable tool for pipeline inspection and quality control.

6.0 RESULTS AND DISCUSSIONS

The results from the experiment and field testing of the caterpillar robot's motion within the pipeline are displayed below. The chart depicts the operation of the electromagnets in the robot's legs, where the X-Axis signifies the robot's travel distance in centimeters, while the Y-Axis signifies the status of the left motor, right motor, and electromagnets, denoting their ON/OFF positions.

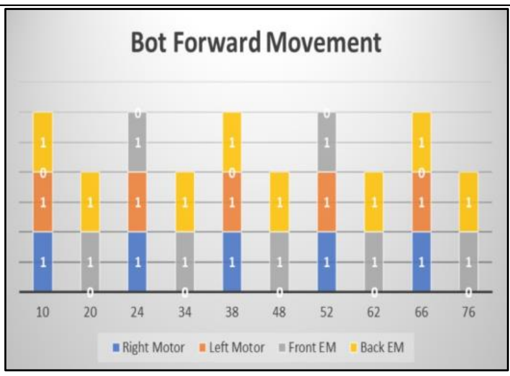

Fig 6.1.1: Forward Movement Chart

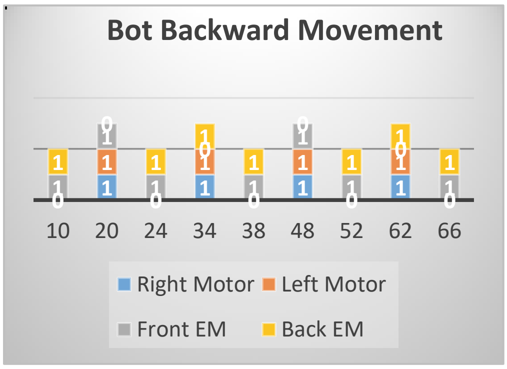

Fig 6.1.2: Backward Movement Chart

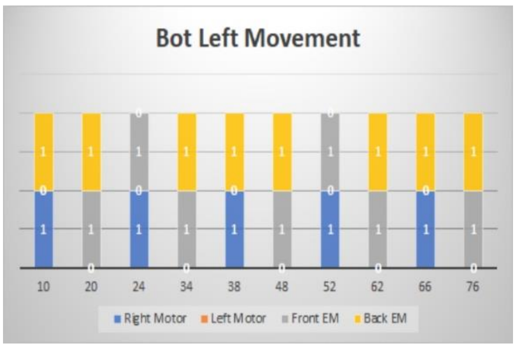

Fig 6.1.3: Left Movement Chart

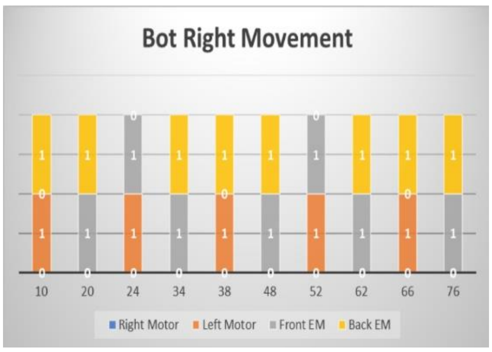

Fig 6.1.4: Right Movement Chart

In this section, the emphasis is on image processing, and the entire programming is carried out in Python using OpenCV and Raspberry pi 4. The model has been specifically trained to recognize signs of corrosion and cracks on the inner surface of pipes.

The explored image processing for a defect-free pipe, including the original image and its corresponding histogram were shown below

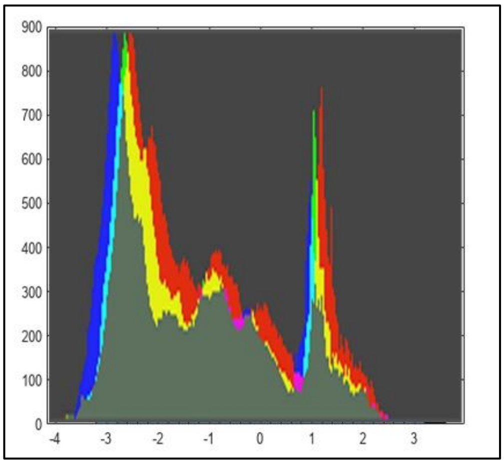

Fig 6.2 a): Image of Good pipe **Fig 6.2 b): Histogram of Good Pipe**

6.1 Corrosion Detection:

The explored image processing for a rusted pipe, including the corrosion image and its corresponding histogram were shown below.

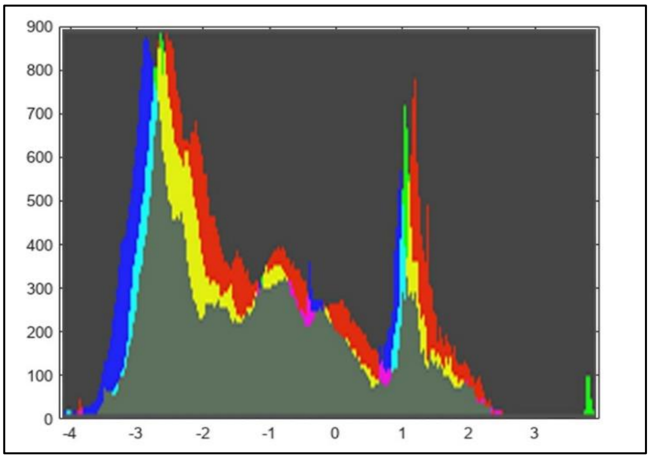

Fig 6.2.1 a): Image of rust in Pipe **Fig 6.2.1 b): Histogram of rusted Pipe**

6.2 Crack Detection

The explored image processing for a crack in pipe, including the crack image and its corresponding histogram were shown below.

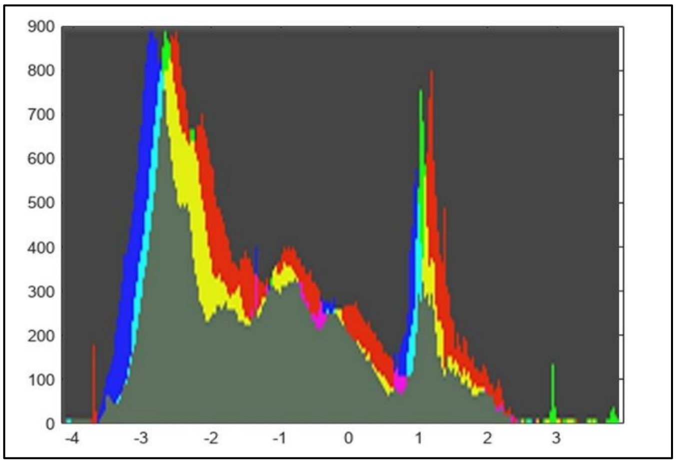

Fig 6.2.2 a): Image of crack in Pipe **Fig 6.2.2 b): Histogram of Cracked Pipe**

CONCLUSION

This research project was primarily focused on the development of an in-pipe inspection robot equipped with caterpillar-like mobility, specifically designed to navigate pipes of varying diameters. What set this project apart was the incorporation of the Haar Cascade algorithm into the image processing framework, enabling the efficient detection of various pipe irregularities, such as corrosion and cracks. By combining innovative design with advanced image processing techniques, this study successfully demonstrated the synergistic approach, resulting in a holistic and effective solution for comprehensive pipe inspection. This approach not only addresses the physical challenges of robotic mobility within pipes but also enhances the robot's capability to identify and report potential issues, making it a valuable tool in pipeline maintenance and safety.

REFERENCES

[1] Dertien, Edwin; Stramigioli, Stefano; Pulles, Kees (2011). [IEEE 2011 IEEE International Conference on Robotics and Automation (ICRA) - Shanghai, China (2011.05.9-2011.05.13)] 2011 IEEE International Conference on Robotics and Automation - Development of an inspection robot for small diameter gas distribution mains. pp, 5044–5049. (2011)

[2] Mohammed, M. N.; Shini Nadarajah, Vidya; Mohd Lazim, Nor Fazlina; Shazwany Zamani, Nur; Al-Sanjary, Omar Ismael; Ali, Musab A. M.; Al-Yousif, Shahad, "Design and Development of Pipeline Inspection Robot for Crack and Corrosion Detection" ,[IEEE 2018 IEEE Conference on Systems, Process and Control (ICSPC) - Melaka, Malaysia (2018.12.14-2018.12.15)] 2018 IEEE Conference on Systems, Process and Control (ICSPC) –. pp 29–32. (2018).

[3] Kim, Jong-Hoon; Sharma, Gokarna; Iyengar, S. Sitharama (2010). [IEEE 2010 IEEE International Conference on Industrial Technology - Vi a del Mar, "FAMPER: A fully autonomous mobile robot for pipeline exploration", Chile (2010.03.14-2010.03.17)] 2010 IEEE International Conference on Industrial Technology –, pp 517–523. (2010)

[4] Alam, Khairul; Ray, Tapabrata; Anavatti, Sreenatha G, "A brief taxonomy of autonomous underwater vehicle design literature", Ocean Engineering, 88(), 627–630. doi: 10.1016/j.oceaneng.2014.04.027, (2014).

[5] Alexander G. Rumson, "The application of fully unmanned robotic systems for inspection of subsea pipelines", Ocean Engineering, Volume 235,2021,109214, ISSN 0029-8018, (2021).

[6] Gómez, Cristina; Green, David R, "Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping", Arabian Journal of Geosciences, 10(9), 202. (2017).

[7] Qiao, Jinwei; Shang, Jianzhong; Goldenberg, Andrew, "Development of Inchworm In-Pipe Robot Based on Self-Locking Mechanism". IEEE/ASME Transactions on Mechatronics, 18(2), pp 799–806. (2013).

[8] K. Kusunose, "Development of Inchworm Type Pipe Inspection Robot using Extension Type Flexible Pneumatic Actuators", Int. J. Automot. Mech. Eng., vol. 17, no. 2, pp. 8019–8028, Aug. 2020.

[9] Qizhi Xiehttps://orcid.org/0000-0002-8818-20261,2, Songyong Liu2
and Xiliang Ma1,
'Design of a novel inchworm in-pipe robot based on cam-linkage mechanism', Advances in Mechanical Engineering
Volume 13, Issue 9, September 2021.

[10] Belyaev, A., Papunin, A., Zharkov, E., Vasiliev, A., Belyakov, V. and Makarov, V. "Experimental Theoretical Study of the Mobile Robotic System Movement with Caterpillar-modular Propulsion on the Beach Line Terrain", In Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2020), pages 567-572.

[11] Abdellatif, Mohamed; Mohamed, Hazem; Hesham, Mohamed; Abdelmoneim, Ahmed; Kamal, Amro; Khaled, Ahmed; Tandon, P.; Wisnoe, W.; bin Abdullah, M.Z. (2018), "Mechatronics Design of an Autonomous Pipe-Inspection Robot", MATEC Web of Conferences, 153 ,(2002).

[12] Lee, Dong-Hyuk; Moon, Hyungpil; Choi, Hyouk Ryeol, "Autonomous navigation of in-pipe working robot in unknown pipeline environment", [IEEE 2011 IEEE International Conference on Robotics and Automation (ICRA) - Shanghai, China (2011.05.9-2011.05.13)] 2011 IEEE International Conference on Robotics and Automation –pp 1559–1564. (2011)

[13] Abdelkader, M., Güler, S., Jaleel, H. et al. Aerial Swarms: "Recent Applications and Challenges. Current Robot Rep 2", 309–320 https://doi.org/10.1007/s43154-021-00063-4, (2021).

[14] Shukla, Amit; Karki, Hamad," Application of robotics in onshore oil and gas industry -A review part I", Robotics and Autonomous Systems, (), S0921889015002006. (2015).

[15]. Oyekola Peter Oluwatosin, Shoeb Ahmed Syed and Owen Apis "Application of Computer Vision in Pipeline Inspection Robots", Proceedings of the 11th Annual International Conference on Industrial Engineering and Operations Management Singapore, March 7-11, 2021.

[16] Nhat-Duc Hoang 1 and Van-Duc Tran 2, "Image Processing-Based Detection of Pipe Corrosion Using Texture Analysis and Metaheuristic-Optimized Machine Learning Approach", Hindawi Computational Intelligence and Neuroscience Volume 2019.

[17] Hoang, Nhat-Duc, "Image Processing-Based Pitting Corrosion Detection Using Metaheuristic Optimized Multilevel Image Thresholding and Machine-Learning Approaches", Mathematical Problems in Engineering, 2020, pp 1–19, (2020).

[18] Aniket Colvalkar ⥣, Sachin S. Pawar, Bhumeshwar K. Patle, "In-pipe inspection robotic system for defect detection and identification using image processing", Materials Today: Proceedings 72, pp 1735–1742, (2023)